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Techno-Economic Analysis of Seawater Freezing Desalination using Liquefied Natural Gas

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This work aims to propose a detailed mathematical model to evaluate the feasibility of a seawater desalination process that is based on the cold energy provided by the regasification of the liquefied natural gas (LNG). Detailed material and energy balance models as well as the basic models for calculation of thermodynamic properties are presented for subsequent Seawater Freezing Desalination (SFD) process optimisation. Current analysis results reveal that the process is affected by multiple variables that need further optimisation. With the assumption of 50 % ice production rate in the ice generator, the SFD system could be able to produce 400 Mt/y of freshwater over the world.

1. Introduction

World Resources Institute predicted that there would be more than two third of the world's populations facing water stress issue in 2040. Figure 1 indicates the situation of the countries facing water stress problem and the indicator score representing the level of water stress problem. The higher the indicator score, the more serious the water stress problem in the country. There are about 77 countries listed above the average line facing high water stress problem. Since the freshwater production tending to decline behind population growth, desalination of seawater has become increasingly important.

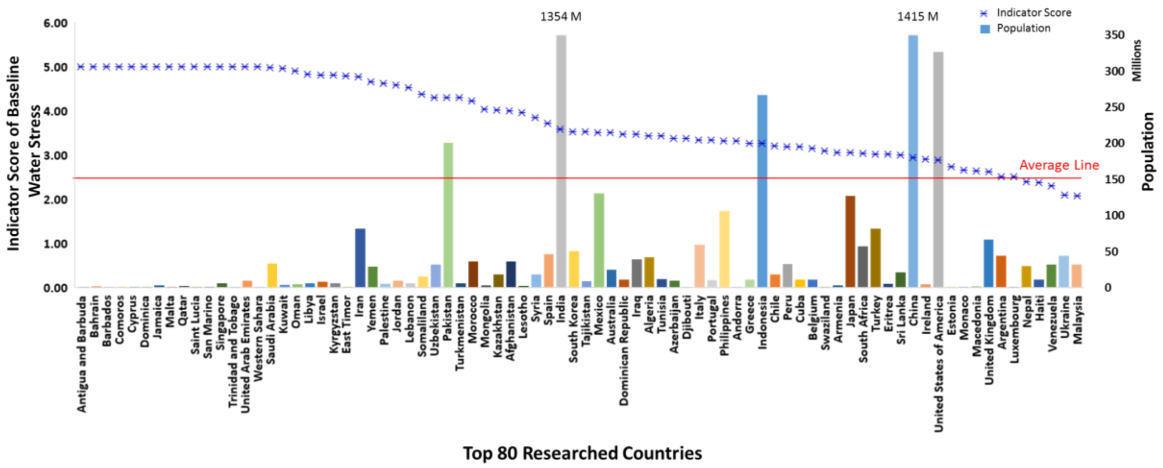

Figure 1: A normalised statistical data about water stress among countries

Natural gas (NG) has been widely used in industries over the world as it has high efficiency and low carbon emission fuels to replace conventional fossil fuels, such as coal and oil. For easy storage for long-distance transport across the oceans, the NG is cooled down to -162 °C and changed into a liquid phase at atmospheric pressure. Liquefied natural gas (LNG) is regasified in the storage terminal by increasing the temperature and

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pressure before it is supplied to the end users. In the regasification process, large amounts of cold energy, including latent heat and sensible heat, about 827 kJ/kg of LNG have been lost through heat exchange between LNG and seawater. Considering the increasing worldwide use of LNG, the potential power that can be recovered from the cold energy up to 258 Mt in 2016 would be approaching 6.8 GW, as shown in Figure 2.

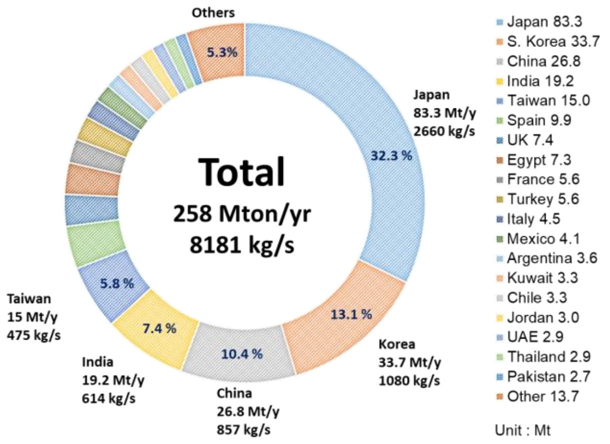


Figure 2: Distribution of LNG importer in 2016 (International Gas Union, 2017)

Before supplying LNG to the end users, LNG cold energy (827 kJ/kg) utilisation during the regasification process is cheap and sustainable energy for Seawater Freezing Desalination (SFD) or electricity generation (Le et al., 2017). SFD is a process that works based on knowledge of the solubility of NaCl in seawater that decreases with temperature. Figure 3 shows that NaCl would be separated when the temperature decreases to -2 ºC causing the seawater turns into freshwater ice and concentrated brine. Therefore, freshwater ice can be obtained when temperature of seawater decreases to -2 ºC. Due to these facts, combining energy loss recovery projects during LNG regasification and seawater desalination processes into a system seems feasible. Therefore, the main purpose of this study is to analyse SFD systems using LNG.

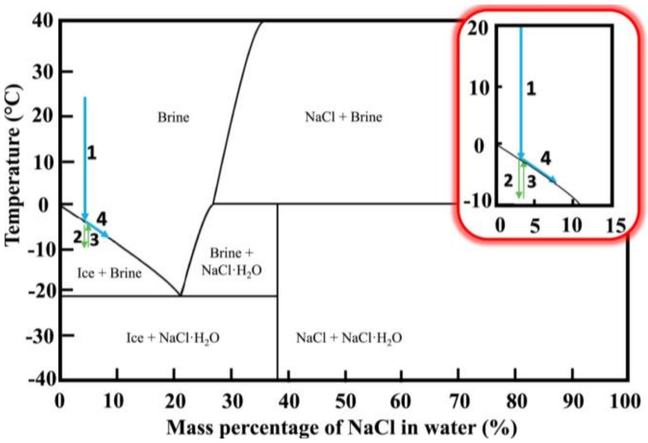


Figure 3: Phase diagram of the NaCl solution (Chung et al., 2016).

2. Seawater freezing desalination systems

Xie et al. (2017) proposed a novel device, a direct contact type ice generator, for seawater freezing desalination using LNG cold energy. Figure 4 shows that the LNG is gasified using the heat supplied by the recirculated warm refrigerant, where most of the thermal energy comes from seawater. The refrigerant releases its energy to heat the LNG and becomes a cryogenic medium for transferring cold energy from the LNG to the direct contact type ice generator to produce freshwater ice, as provided in Figure 5. Washed freshwater ice is sent to an ice melter and experiences heat exchange with seawater to produce freshwater. After the heat exchange, seawater with ice melter is fed into the ice generator to produce ice. An engineering refrigerant, HFE-7100 which main ingredient is methoxy-nonafluorobutane, an almost insoluble organic chemical, has been used in refrigerant circulation of the process (Xie et al., 2017).

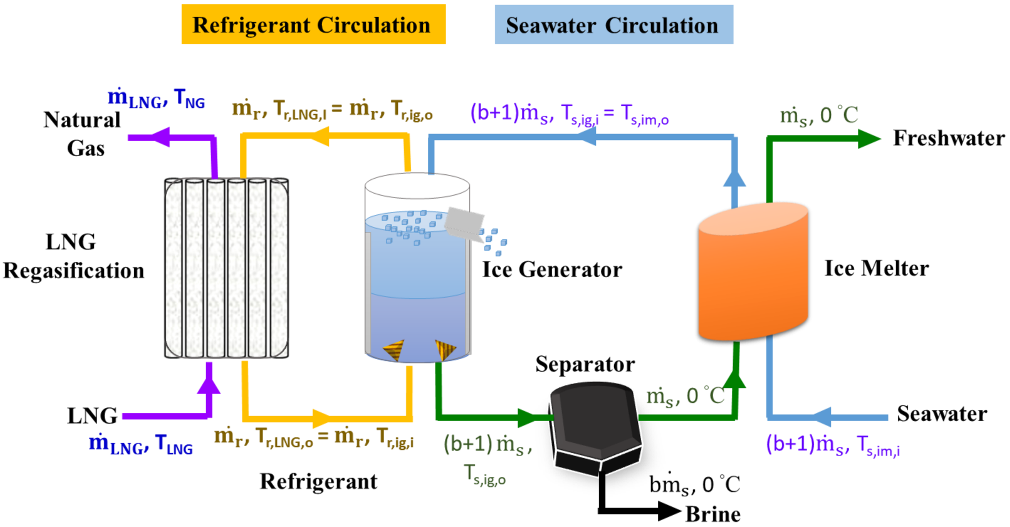


Figure 4: The configuration of seawater freezing desalination process.

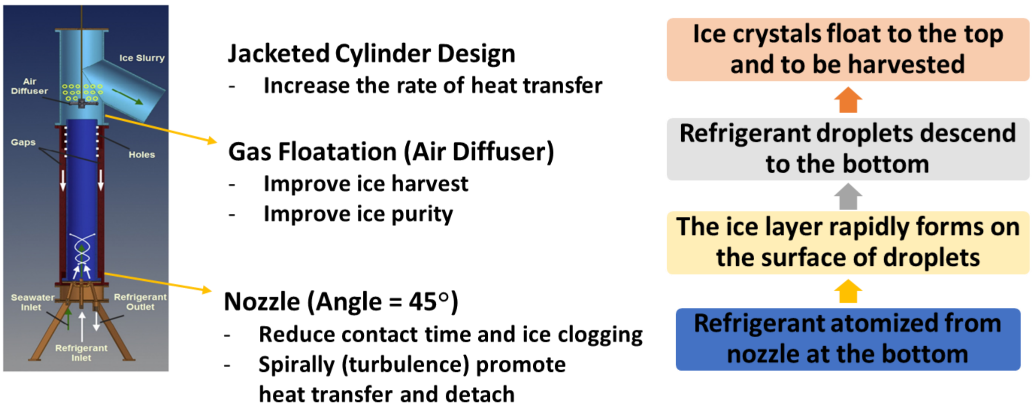


Figure 5: Introduction of direct contact type ice generator (Xie et al., 2017).

Application of a direct contact type ice generator allows physical interaction between seawater and refrigerant by enlarging the heat transfer area and at the same time making the separation process easier.

3. Results and discussions

The present study proposes a detailed techno-economic model for design, analysis, and economic evaluation of the LNG-based seawater freezing desalination process. Detailed material and energy balance models, the basic model for thermodynamic properties calculations, and cost estimation models would be presented for subsequent SFD process optimisation. The analysis results reveal that the process is affected by multiple variables on a basis of the mass flow rate of LNG at 1 kg/s. Figure 6 shows the assumption of ice production rate in the ice generator is 50 %. Table 1 shows the conditions and assumptions of the SFD systems.

Table 1: Conditions and assumptions of the SFD system in Figure 6.

$\dot{m}_{s,HEx}$	$\dot{m}_{LNG}$	$\dot{Q}_{LNG}$	$T_{r,LNG,i}$	$T_{r,ig,o}$	$T_{seawater}$
2.5 kg/s	1 kg/s	827 kJ/s	20 °C	-5 °C	30 °C

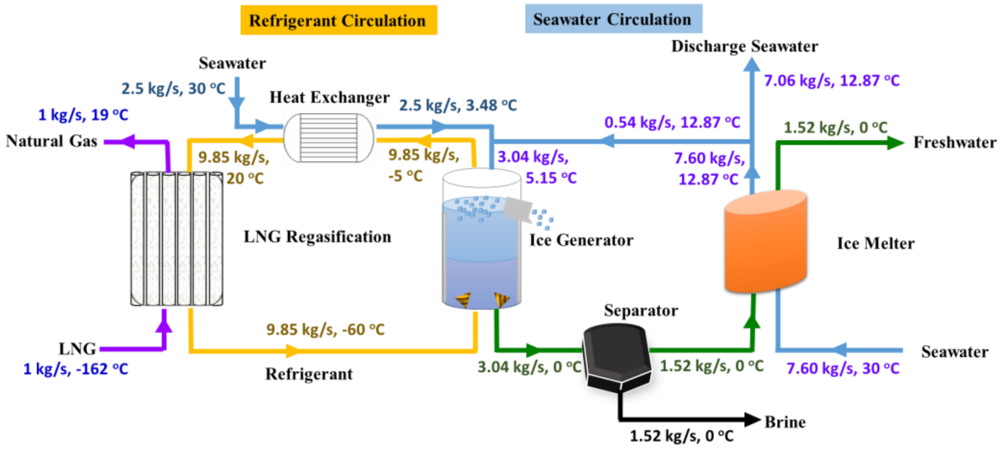


Figure 6: Demonstration of the modified SFD systems under specific conditions

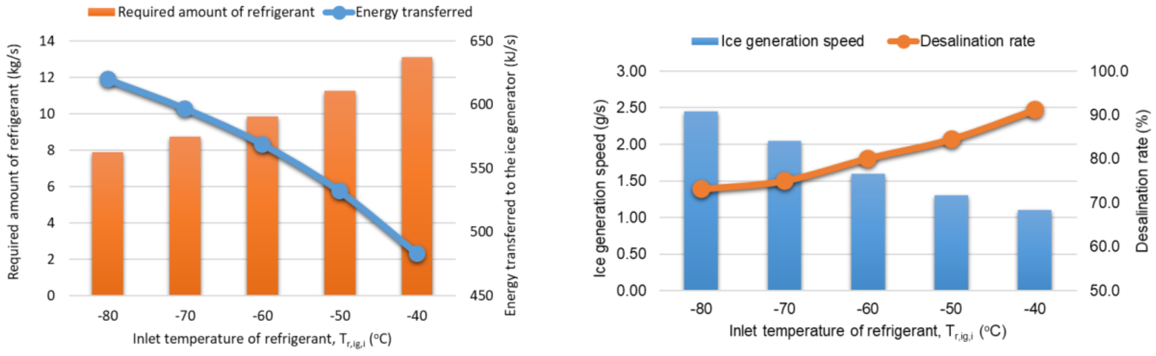
Xie et al. (2017) observed that the energy transferred from LNG to the refrigerant is always maintained at 827 kJ/s. After the calculation, some modifications have been introduced to the system. Since the cold energy recovered from the LNG regasification process is fixed, the amount of freshwater ice produced by ice generators is limited. After the heat exchange with the ice melter, the seawater will be partially discharged before it is delivered to the ice generator. The recirculated insoluble refrigerant is expected to be reused in the system for a long time. The amount of refrigerant will influence the cost of capital. Therefore, the heat exchanger is added to the refrigerant circulation part of the system to minimise the required amount of refrigerant in the process.

$$\dot{Q} = \dot{m} c_p \Delta T \quad (1)$$

The required amount of a particular refrigerant depends on the inlet temperature of warm refrigerant to the regasification unit, provided that the energy transferred, and the outlet temperature of the refrigerant remains constant. From Eq(1), the mass flow rate $\dot{m}_r$ is inversely proportional to the inlet temperature of refrigerant $T_{r,LNG,i}$, when the energy $\dot{Q}_{LNG}$, specific heat capacity $c_{p,r}$ and the outlet temperature $T_{r,LNG,o}$ remain constant. In other words, the higher the $T_{r,LNG,i}$, the lower the $\dot{m}_r$ needed. As a result, the refrigerant output stream from the ice generator is heated by external seawater up to 20 °C before it is delivered to the regasification unit. After heat exchange with refrigerant, the temperature of seawater is much lower than seawater from ice melter. Therefore, cooler streams are more suitable to be delivered to the ice generator as a raw material for freshwater ice production. Most of the seawater entering the ice generator is from the heat exchanger stream. Only small contributing amounts are from the ice melter, where most of the seawater is discharged.

Figure 6 indicates that 9.85 kg/s of refrigerant and 10.1 kg/s of seawater are required to produce 1.52 kg/s of freshwater in the system on the basis of 1 kg/s LNG. At this scale, the annual production of freshwater is 43.78 M kg assuming that the operating time per year is 8,000 h. The main factors affecting the system are the temperature of the refrigerant $T_{r,ig,i}$ and the temperature of the seawater entering the ice generator $T_{s,ig,i}$. Results generated under various conditions are discussed in the following figures.

The effects of $T_{r,ig,i}$ to the system are shown in Figures 7(a) and 7(b), where the last experimental results were obtained from Xie et al. (2017). Based on the calculations in Figure 7(a), the cold energy recovered from the LNG regasification process by the refrigerant would not be 100 % transferred to the ice generator even under ideal conditions due to heat loss caused by heat exchange between materials with different values of specific heat capacities (c_p). When $T_{r,ig,i}$ increases from -80 °C to -40 °C, the transferred energy decreases from 75 % to 58 % and the required amount of refrigerant increases from 7.88 kg/s to 13.13 kg/s. In other words, a higher amount of energy is transferred, a lower amount of seawater is required when the inlet temperature of the refrigerant is lower. In contrast, the desalination rate, which represents the purity of the produced freshwater ice, obviously descends although the ice generation speed increases while $T_{r,ig,i}$ decreases, as shown in Figure 7(b). Seawater will be generated into ice at a faster rate as the temperature dramatically decreases, but high-speed crystallisation can cause the salts enclosed within ice due to irregular structure. Accordingly, it would be a trade-off among the requirements of seawater, energy transferred, ice generation speed, and the purity of freshwater ice produced in the system.



(a) (b)

Figure 7: Effect of (a) $T_{r,ig,i}$ to the system and (b) $T_{r,ig,i}$ on freshwater ice production (Xie et al., 2017)

According to the calculations on a basis of 1 kg/s LNG in Figure 8, the amount of required seawater $k\dot{m}_s$ increases from 8.67 kg/s to 17.35 kg/s as the $T_{s,ig,i}$ increases from 4.45 °C to 6.32 °C. The results are reasonable as large amounts of seawater are used for melting the ice and the amount of ice produced per kg LNG at different temperatures is almost the same in this scale. The more the amount of seawater introduced into the system, the higher the $T_{s,ig,i}$. In addition, the trend of discharge seawater is similar to the required seawater, which is increasing from 5.59 kg/s to 14.38 kg/s. The ice produced per kg LNG is half the amount of seawater entering the ice generator as a result of the 50 % ice production rate assumption, which is introduced previously.

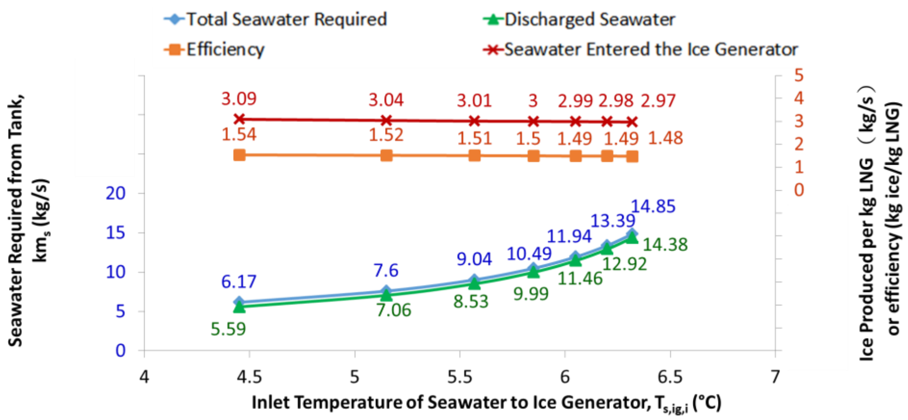


Figure 8: Effect of $T_{s,ig,i}$ to the system

For the SFD process, the volume of ice generator is the crucial point in the economic evaluation. The results illustrated in Figure 9 are calculated with Equation (2) and Equation (3) listed below.

$$\Delta T_{lm} = \frac{(T_{s,ig,i} - T_{r,ig,i}) - (T_{ice} - T_{r,ig,o})}{ln(T_{s,ig,i} - T_{r,ig,i}) - ln(T_{ice} - T_{r,ig,o})} \qquad (2)$$

$$V_{ig} = \frac{Q_{LNG}}{U_v \Delta T_{lm}} \qquad (3)$$

Figure 9 shows the volume of the ice generator decreases as the $T_{s,ig,i}$ increases from 4.45 °C to 6.32 °C under a constant $T_{r,ig,i}$. Meanwhile, the volume of the ice generator increases as the $T_{r,ig,i}$ increases from -80 °C to -40 °C under a constant $T_{s,ig,i}$. The volume of ice generator becomes larger as the $T_{s,ig,i}$ and $T_{r,ig,i}$ decreases due to higher production of freshwater ice. In fact, as the ice generator is a novel device that has not been developed into the industrial scale yet and the capital cost is still not estimable in current situation, as a consequence the objective of economic evaluation for the process is to determine the maximum capital cost of ice generator while the system is profitable. This will be the near future work.

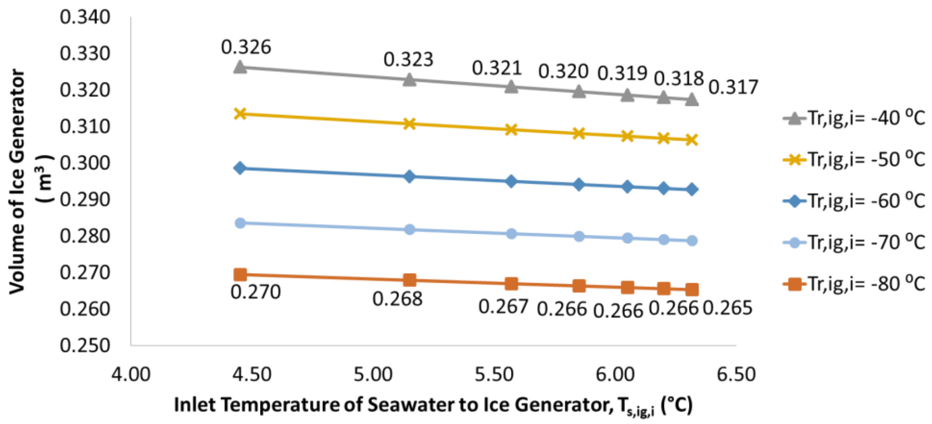


Figure 9: Effect of $T_{s,ig,i}$ to the volume of ice generator

4. Conclusions

In this research, the detailed-analysis of the SFD system based on Xie et al. (2017) has been done according to the principles of heat and mass balance (Gundersen et al., 2009). As there is a number of variables in the system, some conditions and assumptions should be fixed to decrease the degree of freedom in the system. The data shown in Figure 2 shows that the SFD system is able to produce 392.2 Mt of freshwater per year in the world using industrial scale, which is shown in Figure 6. The research is believed to have high potential in reducing water stress issues that contributes to the human life by producing water resources. In future studies, estimation of energy consumption for the whole system, especially for the amount of energy required by the pump would be calculated as it would be the largest part of the utility, which mainly affects the operating costs of the system. For safety purposes, plantwide process control would be performed by adding controllers and valves to the system. Finally, process integration and optimisation for the system would be performed to ensure the efficiency of energy utilisation is optimal. The economic evaluation would be introduced in the last part of research.

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